CosmiX and beyond:

Simulating particle tracks in image sensors and microelectronics

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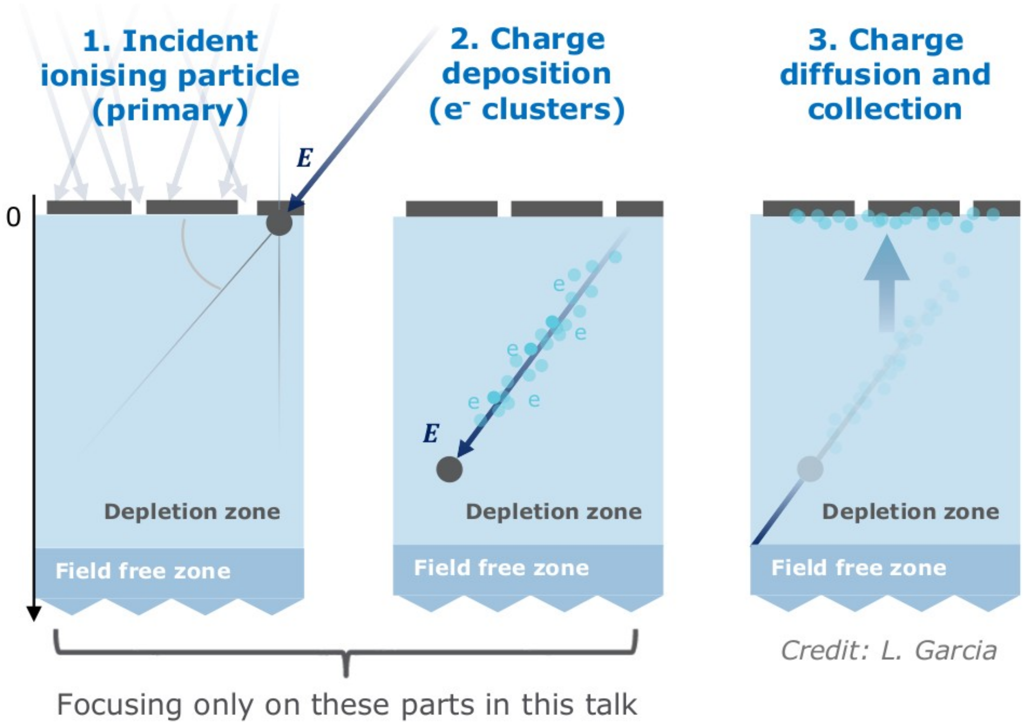
[1] CERN Radiation To Electronics (R2E) project
[2] ESA/ESTEC Science Payload Validation

Detector Modelling workshop
16 June 2021

Single events in semiconductors

- Single ionising particle directly* deposits charge inside a thin sensitive volume in a stochastic way



Credit: L. Garcia

Particle energy and direction

Location of interactions along particle track

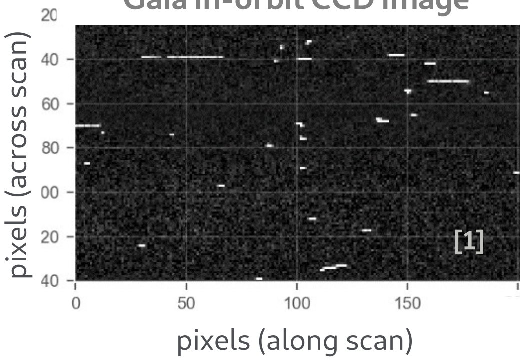
Amount of charge deposited (total and per interaction)

Monte Carlo simulations

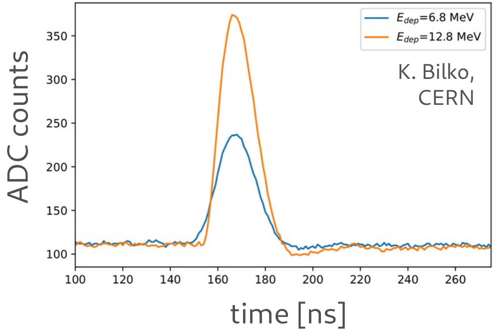
* ignoring indirect deposition via nuclear reactions

Single events in semiconductors

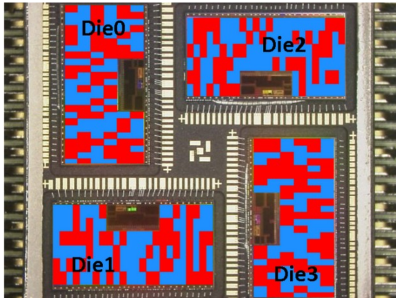
Gaia in-orbit CCD image



Silicon diode detector signals



ESA Single Event Upset monitor



M. Cecchetto, CERN

Cosmic Ray (CR) Track

- Space Astronomy
- Imaging sensors (CCD, CMOS)
- Image artifact
- Affecting Gaia photometry, Euclid galaxy shape measurements, etc.
- Removal during on-board/offline data-processing

Particle Detector Signal

- Particle & Nuclear Physics
- Solid-state particle detectors
- Scientific data
- Tracking charged hadrons around LHC interaction points
- Detection efficiency enhancement

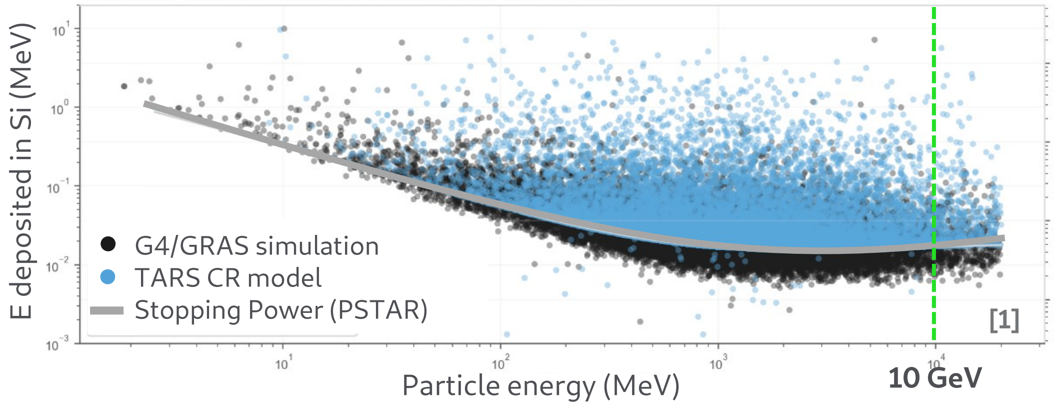
Single Event Effect (SEE)

- Radiation & Electrical Engineering
- Microelectronic devices
- Soft/Hard error in circuit
- Causing premature LHC beam dumps and spacecraft failures
- SEE mitigation, Radiation hardening by design

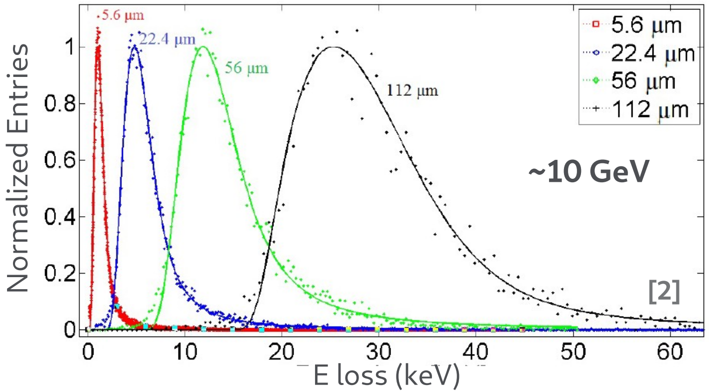
Motivation

- **Monte Carlo particle transport codes** (Geant4, FLUKA) can reproduce both the radiation environment and energy deposited on detector level, but too complex (difficult to learn, install, integrate), and not easy to score/extract data to make CR images ⇒ not optimal for astronomy applications
- There was **hardly any simple, fast and sufficiently accurate tool for CR imaging** → new model for Pyxel!
  - Often **Stopping Power (dE/dx) curves used wrongly** to model single CR tracks in a deterministic way → Example: training of Gaia on-board CR rejection algorithm

Energy deposited: Model vs. Reality

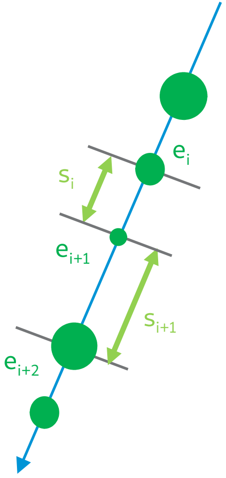


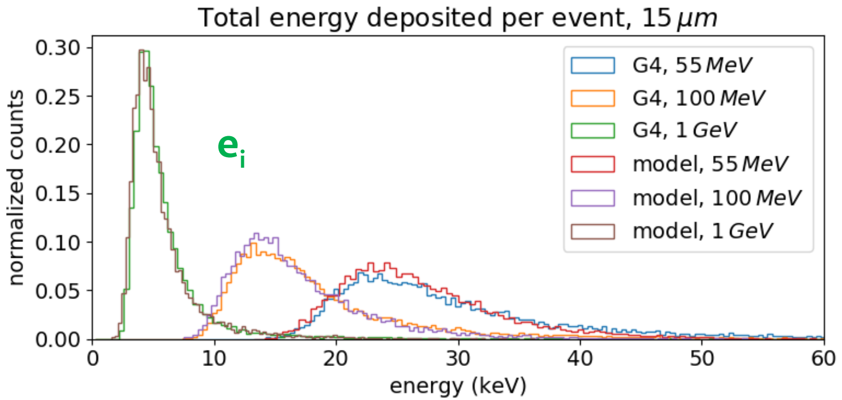
Proton energy loss straggling



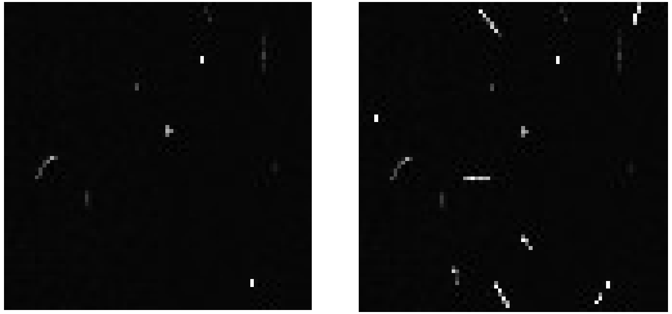
CosmiX – A novel cosmic ray model

- **Goal:** Generate **statistically correct CR tracks** regarding both **photometry** (charge amount) and **morphology** (shape, location, orientation)
- **Idea:** Only **size** and **location of e^- clusters** are needed along the primary trajectory
- Simple **multi-group Monte Carlo** algorithm
- Sampling **E deposition distributions** of thin layers **pre-generated** with a dedicated Geant4 application for each energy group (per particle species per material)
  - To be replaced by analytically generated, parametric Landau distributions
- **Open-source code**, implemented in **Python**, latest version here on Gitlab.com!



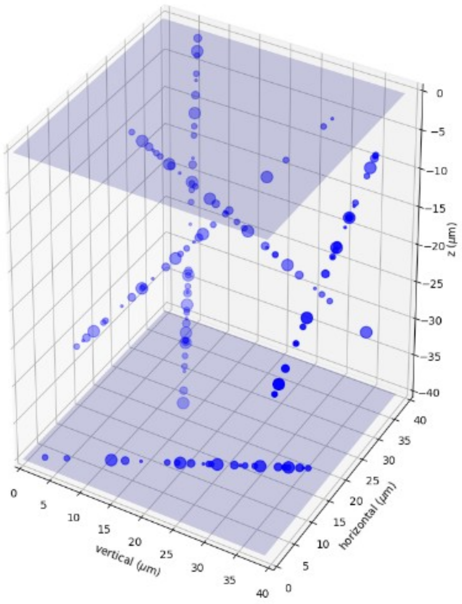


Gaia CCD CR tracks + CosmiX tracks added



CosmiX – Model assumptions & limitations

- **Only EM interactions** (mostly direct ionisation)
- Primary particles: only protons yet (but others can be added)
- Detector material: only silicon yet (but others can be added)
- **E_{loss} of primaries is negligible** within thin layers ($dE/dx \approx 0 \rightarrow$ MIP)
  - ⇒ Monoenergetic primaries in 10 MeV-10 GeV energy range
- **$E_{dep, total} \approx \Sigma_k E_{dep,k}$** in k thin layers with l_{char} **characteristic length**
  - ⇒ Ionisation occurs maximum once after each l_{char} distance travelled by primary particle
- Most of the charge generated by secondary δ and Auger electrons with short ranges
  - ⇒ All **electrons can be grouped into clusters** around secondary vertices
  - ⇒ Clusters are **point-like** (charge diffusion not included in model)
  - ⇒ Cluster locations are **uniformly distributed** along the particle steps
- E_{dep} / n_{dep} = Mean e^- - h^+ pair creation energy (3.6 eV in Si)



CosmiX tracks with clusters in 3D

CosmiX – Inputs & Outputs

Application / Framework (Pyxel)

Inputs
- Volume dimensions
- Volume material
- Energy / Spectrum
- Characteristic length
- Particle number
- Starting position
- Beam direction
- Output folder
- Random seed

CosmiX

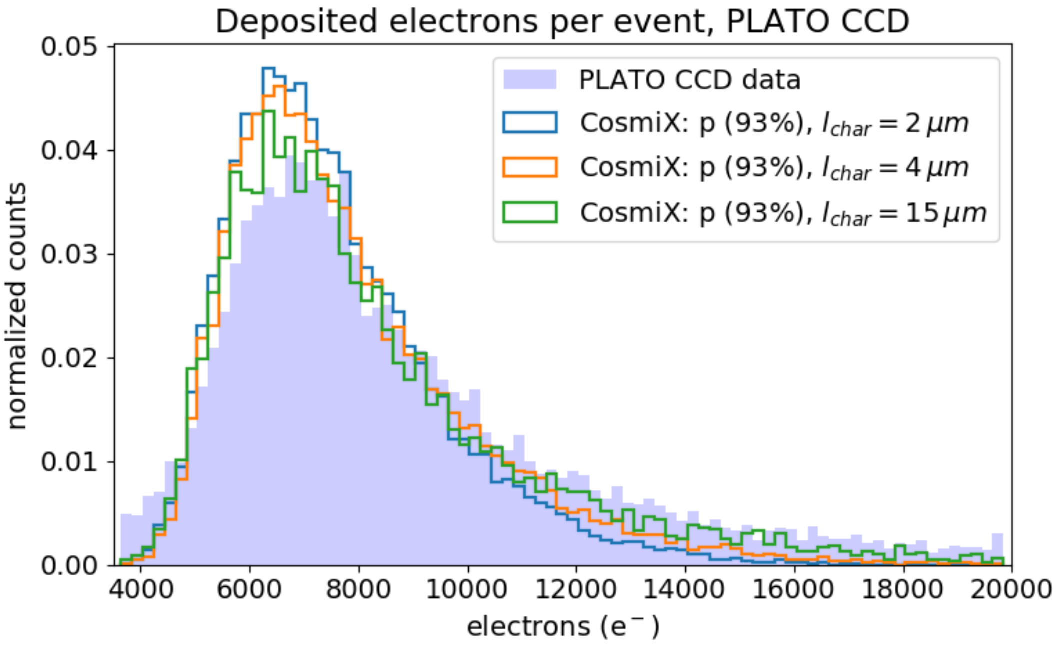
Outputs
List of charge clusters:
- Sizes [e^-]
- X positions [µm]
- Y positions [µm]
- Z positions [µm]

CosmiX validation with PLATO CCD data

- **CosmiX results are in good agreement with irradiated PLATO CCD data**
- Collimated, perpendicular **proton beam**
- Only one energy group used: **55 MeV**
- Closer the l_{char} to the CCD's actual thickness, the more accurate the distribution, but it results fewer clusters (small trade-off between accuracy of CR shapes and cluster sizes)

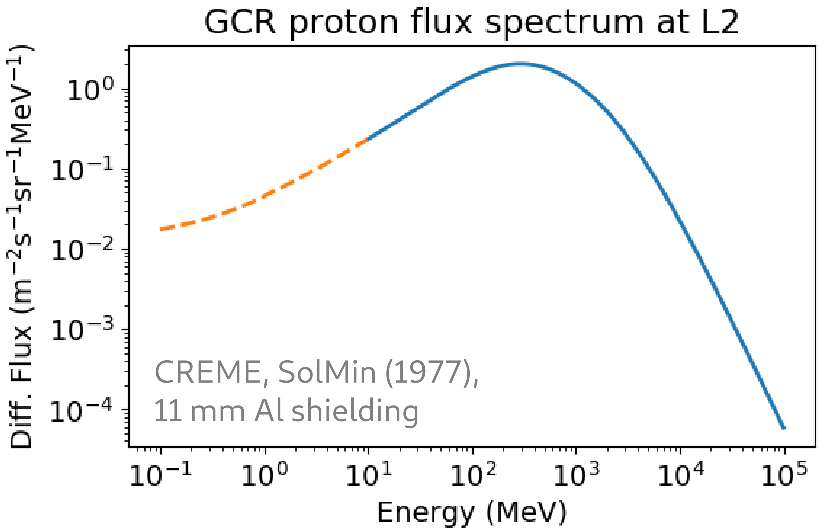
Irrad. PLATO CCD tracks

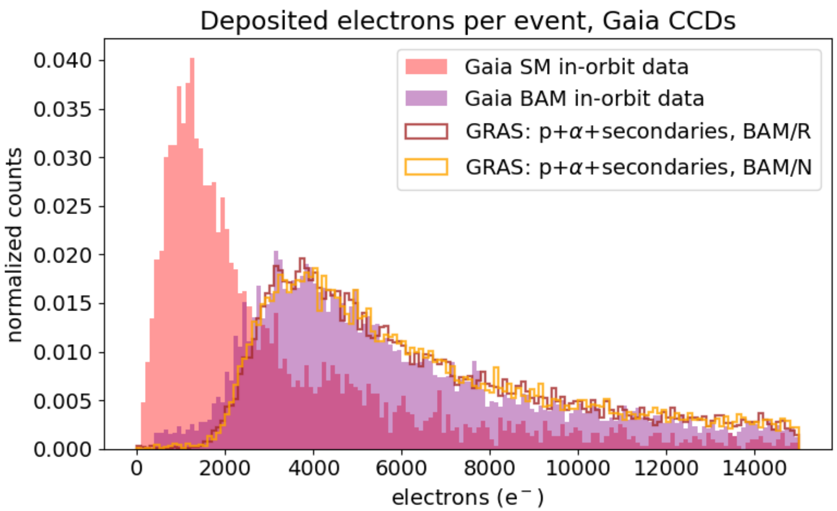
CosmiX tracks

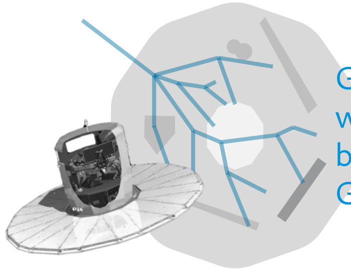


PLATO CCD irrad. data analysed by T. Prod'homme (ESA)

Detailed MC simulations of in-orbit Gaia CCDs

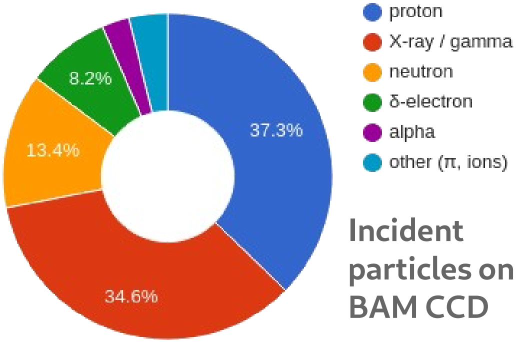




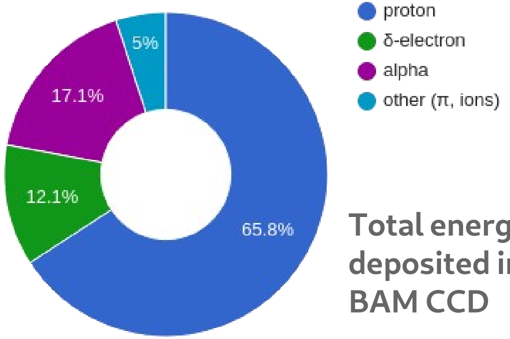


GRAS simulations were performed by M. Vuolo and G. Santin (ESA)

GRAS: Geant4 Radiation Analysis for Space (ESA)



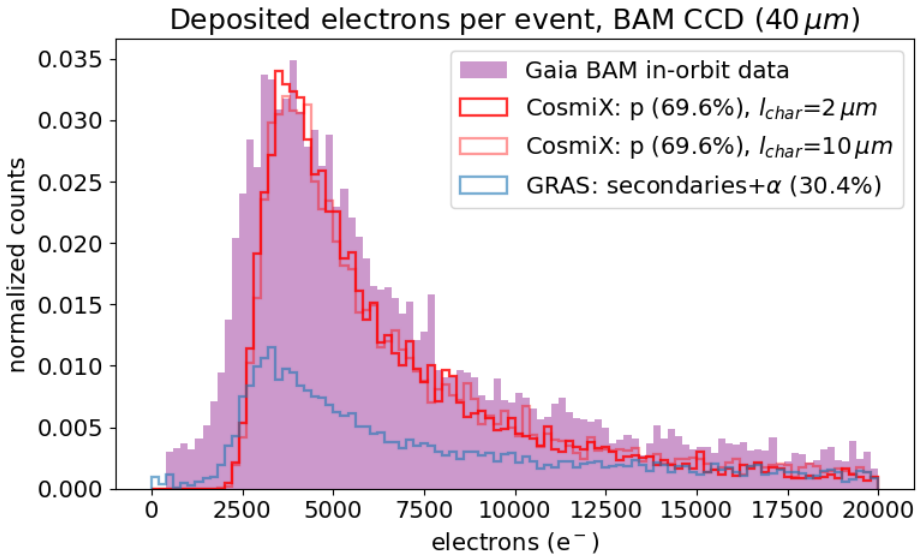
Incident particles on BAM CCD

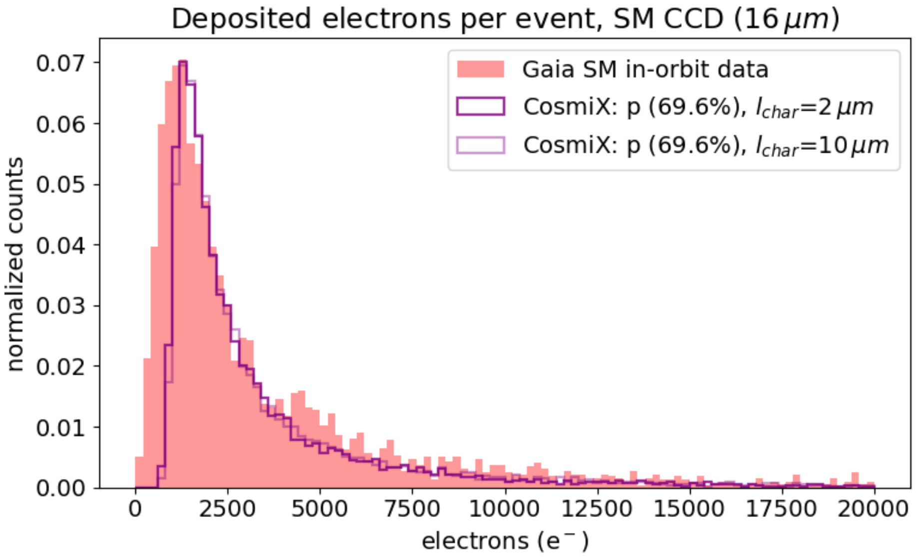


Total energy deposited in BAM CCD

CosmiX validation with Gaia CCD data

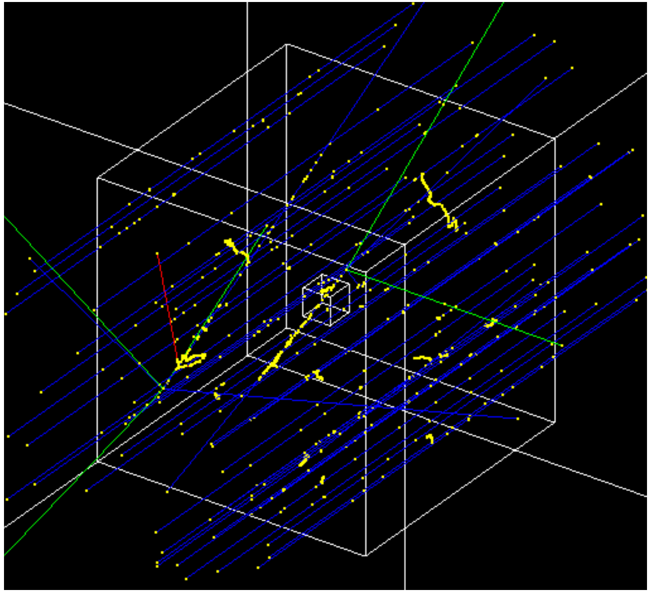
- Proton CR tracks simulated with **CosmiX** and spectra compared **with Gaia BAM and SM CCD data**
- Collimated, perpendicular p beam with GCR spectrum (10 MeV-10 GeV range, ≤355 energy groups used)
- Single events were caused by **GCR protons only in 69.6%** (the rest: secondaries and GCR α)
- **CosmiX results are in good agreement with in-orbit Gaia CR data** (both from BAM and SM CCDs)





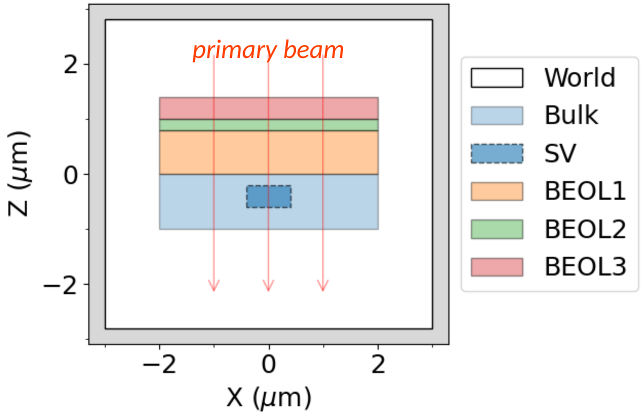
G4SEE – A novel SEE MC simulation toolkit

- G4SEE Single Event Effect simulation tool(kit) is based on Geant4 Monte Carlo particle transport toolkit
- Goal: score and process all information relevant for SEEs on an event-by-event and particle-by-particle basis inside micrometric volumes (according to users' needs), mainly direct and indirect energy deposition distributions
- Developed for and by the radiation effects (incl. CERN R2E) community, fully open-source and accessible soon via **https://cern.ch/g4see**
- Primarily focusing on (but not limited to) SEEs by neutrons (< 20 MeV), protons indirectly (100 keV-200 MeV), later high-LET and UHE heavy ions
- Validation ongoing with neutron and proton irradiation tests
- Not just for electronic components, but for detectors too



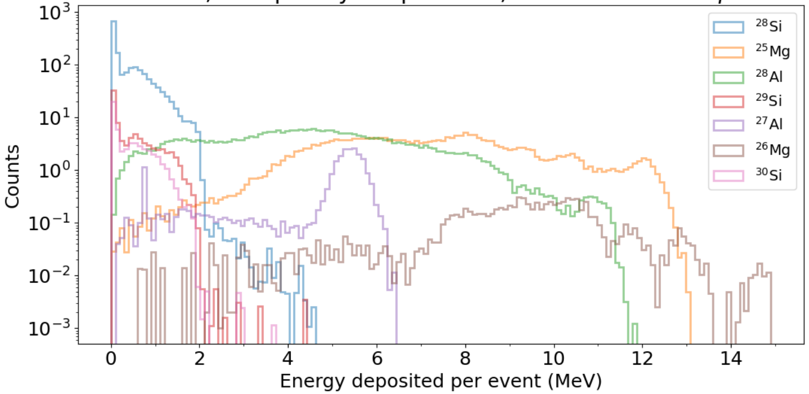
G4SEE – A novel SEE MC simulation toolkit

G4SEE geometry (x-z view)

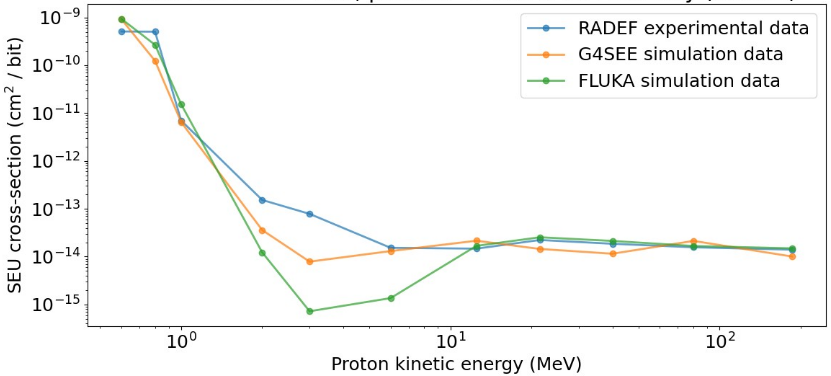


A user-defined multi-layer target geometry and materials of a microelectronic cell (e.g. SRAM memory), including an SEE Sensitive Volume (SV) and 3 back end of line (BEOL) layers

G4SEE Detailed, Grouped by ion products, 14.8MeV n → 300μm Si diode



G4SEE vs. RADEF test, protons → ISSI SRAM memory (310nm)



CosmiX open-source python code on Gitlab.com:

>> gitlab.com/david.lucsanyi/cosmix <<

Feel free to use, share and **contribute** to CosmiX!

Thank you for your attention!

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Thibaut Prod'homme, **thibaut.prodhomme@esa.int**

References

This work:

Dávid Lucsányi; Thibaut Prod'homme: "Simulating Charge Deposition by Cosmic Rays Inside Astronomical Imaging Detectors", IEEE TNS Vol. 67 (July 2020), https://ieeexplore.ieee.org/abstract/document/9058640

[1] L. Garcia et al.: „Validation of a CCD cosmic ray event simulator against Gaia in-orbit data", SPIE Proceedings Vol. 10709 (2018)

[2] S. Meroli et al.: „Energy loss measurement for charged particles in very thin silicon layers", JINST 6 P06013 (2011)

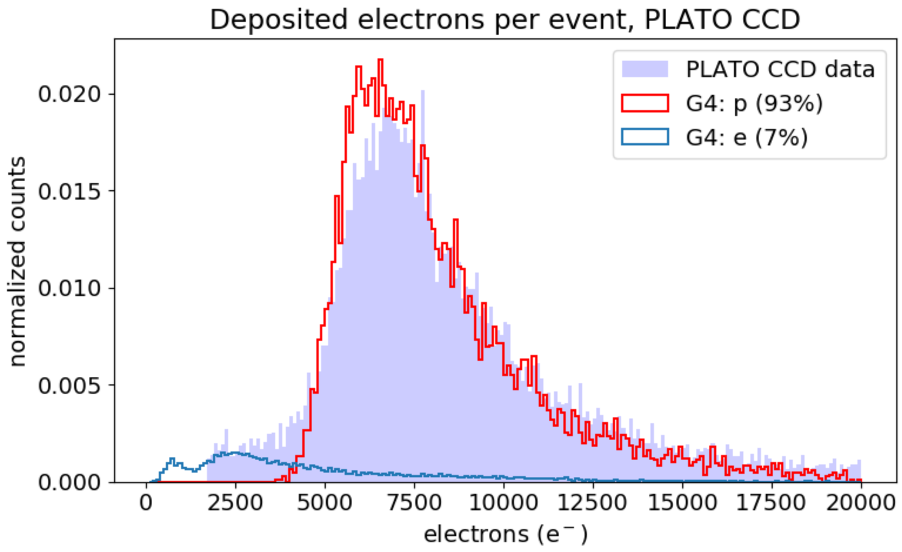
[3] T. Prod'homme et al.: „Comparative Study of Cryogenic Versus Room-Temperature Proton Irradiation of N-Channel CCDs and Subsequent Annealing", IEEE TNS Vol. 66 (2019)

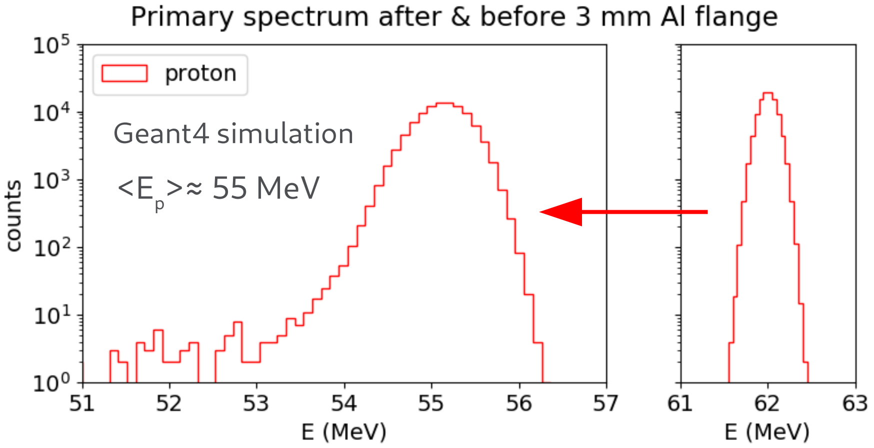
[4] P. G. van Dokkum: „Cosmic-Ray Rejection by Laplacian Edge Detection", PASP 113, 1420 (2001)

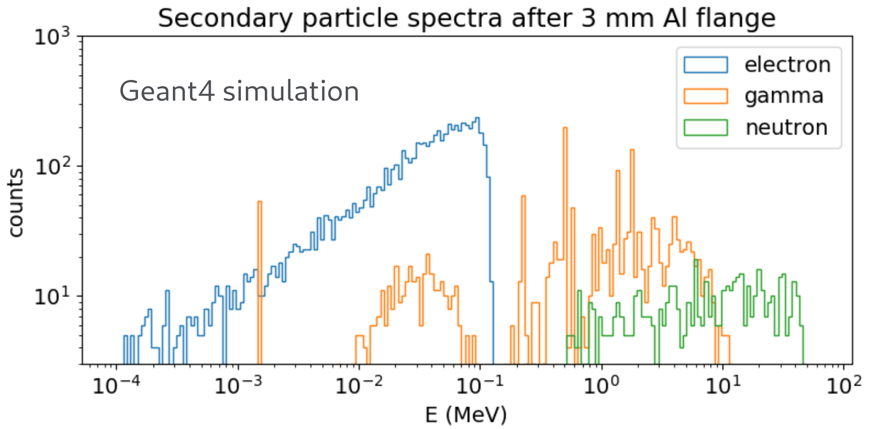
Backup slides

PLATO CCD irradiation test

- Cryogenic & RT irradiation at UCL LIF [3]
- Single Events separated using **L.A.Cosmic tool** [4]
- Proton beam degraded to **55 MeV** (through 3 mm Al)
- **Geant4 simulations**: Single events caused in ~**93% by protons** and ~**7% by δ-electrons**

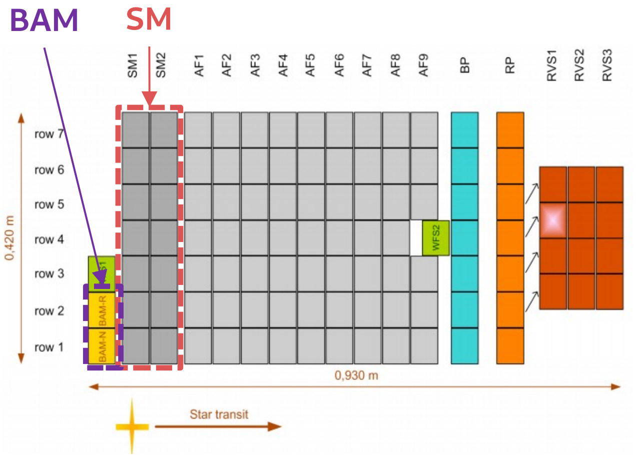






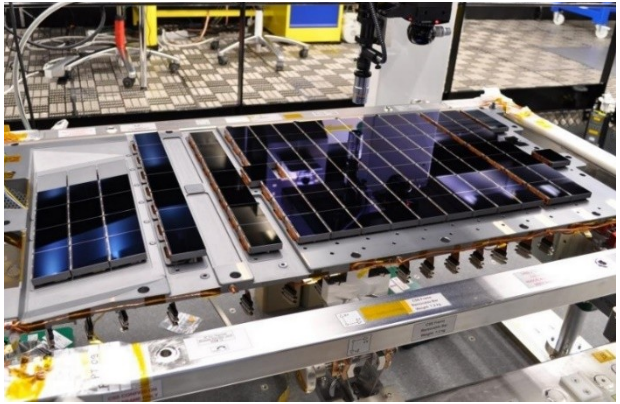
Instruments of Gaia space observatory

- Gaia is currently operating in-orbit around L_2, surveying billion stars in the Milky Way
- **Basic Angle Monitor (BAM)**: 40 μm Si CCD; **Sky Mapper (SM)**: 16 μm Si CCD
- SiC radiator and other materials around focal plane ⇒**CR shielding and collimation**
- CR signals were separated from raw CCD data using **L.A.Cosmic** algorithm [4]

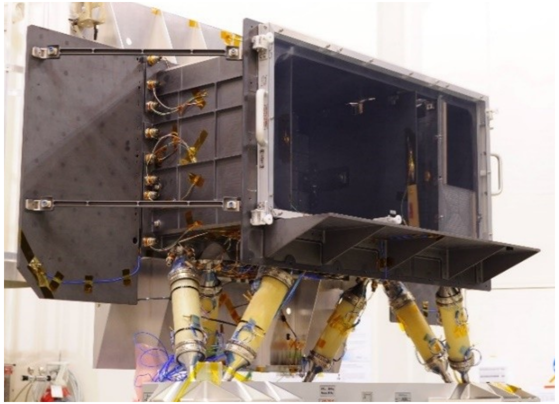


Credit: A. Short, J. de Bruijne

Gaia Focal Plane



Gaia SiC radiator assembly



Credit: EADS Astrium / Airbus

CosmiX use case: MCT detector optimization

- H2RG with 8 m cut-off, $Hg_{0.75}Cd_{0.25}Te$ (MCT) alloy **grown on CdZnTe (CZT) substrate**
- MCT has much **higher Z elements** than Si ⇒ More charge deposited by cosmic rays
- Need to **optimise MCT & CZT substrate thickness** regarding CR charge deposition